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Effects of the roots of *Cynodon dactylon* and *Schefflera heptaphylla* on water infiltration rate and soil hydraulic conductivity

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Abstract

Water infiltration rate and hydraulic conductivity in vegetated soil are two vital hydrological parameters for agriculturists to determine availability of soil moisture for assessing crop growths and yields, and also for engineers to carry out stability calculations of vegetated slopes. However, any effects of roots on these two parameters are not well-understood. This study aims to quantify the effects of a grass species, *Cynodon dactylon*, and a tree species, *Schefflera heptaphylla*, on infiltration rate and hydraulic conductivity in relation to their root characteristics and suction responses. The two selected species are commonly used for ecological restoration and rehabilitation in many parts of Asia and U.S. A series of in-situ double-ring infiltration tests was conducted during a wet summer, while the responses of soil suction were mointored by tensiometers. When compared to bare soil, the vegetated soil has lower infiltration rate and hydraulic conductivity, due to the clogging of soil pore by plant roots. This results in at least 50% higher suction retained in the vegetated soil. It is revealed that the effects of root-water uptake by the selected species on suction were insignificant due to the small evapotranspiration (< 0.2 mm) when the tests were conducted under the wet climate. There appears to have no significant difference (less than 10%) of infiltration rates, hydraulic conductivity and suction retained between the grass-covered and the tree-covered soil. However, it is identified that the grass and tree species having deeper root depth and greater root area retained higher suction.

Keywords: water infiltration rate, hydraulic conductivity, vegetation, soil suction

Introduction

In a hydrological cycle, water infiltration rate and hydraulic conductivity of vegetated soil are two important parameters governing surface runoff, soil moisture/soil suction in vadose zone and recharge of groundwater table. Quantifying the two hydrological parameters and the associated suction response in soil are important for ecologists to figure maintenance of ecosystems such as wetlands (Eldridge and Freudenberger, 2005; Colloff et al., 2010), and for engineers to analyze suction distribution for stability calculations of vegetated soil slopes (Indraratna et al., 2006; Genet et al., 2010). Water infiltration rate and hydraulic conductivity of vegetated soil are also crucial for agriculturists to determine the availability of soil moisture for assessing crop yields and to more accurately devise irrigation schedule (Wetzel and Chang, 1987; Zhang et al., 2004). However, any effects of plant roots, due to clogging of soil pore (Gabr et al., 1995; Scanlan and Hinz, 2010) or/and water uptake (Feddes et al., 1978; Ng et al., 2013) on the two important hydrological parameters are not well-understood. Quantitative measurements of any of such effects of plant roots on both infiltration rate and hydraulic conductivity of vegetated soil are rare.

Several past studies have been conducted to measure infiltration rates in soil vegetated with different grass species, but the test results seem not to be conclusive. It was found that infiltration rates in grass-covered soil can be higher (van Noordwijk et al., 1991; Mitchell et al., 1995) or lower (Gish and Jury, 1983; Huat et al., 2006; Ng et al., 2014) than those in bare soil. Infiltration rates in grass-covered soil were lower when roots were actively growing, but they were higher when mature roots were decaying. However, it should not be overlooked that higher infiltration rates found in natural soil were prone to be affected by preferential flow along surface cracks due to excessive soil shrinkage in the field (Simon and Collison, 2002; Leung et al., 2011; Ghestem et al., 2011; Leung and Ng, 2013), regardless the plant age.

In order to better interpret water infiltration rate, it may be useful to monitor also the associated changes of soil suction upon infiltration. It is known that the amount and rate of water infiltration in transient state primarily depends on soil hydraulic properties, including soil water retention and hydraulic conductivity (Inoue et al., 2000; Vogel et al., 2000). Knowing the responses of suction in association with infiltration is therefore important because suction is well-recognized as one of the key stress-state variables (Coleman, 1962) governing the behavior of unsaturated soil including the two hydraulic properties (Ng and Leung, 2012). However, most infiltration tests conducted in vegetated soil lacked simultaneous monitoring of soil suction. Without determining the associated responses of suction (and hence hydraulic gradient), infiltration rate measured from a test could not be usefully utilized to further estimate hydraulic conductivity through Darcy's law. Although some field studies included measurements of both infiltration rates and responses of suction (Rahardjo et al., 2005; Huat et al., 2006), they were conducted on natural vegetated soil slopes. This means that the suction recorded can be potentially affected by three-dimensional water flow, from which is not easy to isolate the vegetation effects for accurately interpreting infiltration rates.

Results from limited experiments have revealed that the growth of plant roots would have occupied soil pore space and hence modified soil hydraulic conductivity (Gabr et al., 1995; Buczko et al., 2007; Scanlan and Hinz, 2010). Such modification depends on root characteristics (such as root depth and root diameter) present in the soil. The observed effects of pore clogging by plant roots on soil hydraulic conductivity are species-specific and could not be generalized to other species. In the literature, most findings of root-induced change of soil properties were derived from crop species such as grain and maize. Their root characteristics, and hence the impact on any change of soil hydraulic properties, may be different from the natural species that are used for the purposes of ecological restoration and rehabilitation. However, rare field study is available to quantify water infiltration rate, hydraulic conductivity, and the associated suction responses in soil vegetated with this kind of natural species.

In order to improve our understanding on the effects of roots on water infiltration rates, hydraulic conductivity and the associated suction distributions, a series of three repeated in-situ double-ring infiltration tests (i.e., Inf1, Inf2 and Inf3) were carried out in vegetated soil in this study during a wet summer. Two species, *Cynodon dactylon* (grass) and *Schefflera heptaphylla* (tree), which are commonly found in many parts of Asia such as Hong Kong, Malaysia and U.S. for ecological restoration purposes, were used for testing. In each test, constant-head ponding was applied on ground surface, during which the water volume infiltrated and distributions of suction were monitored by tensiometers. The suction measurements are used to determine hydraulic gradient for estimating hydraulic conductivity of vegetated soil. By comparing the test results obtained from bare and vegetated soil, any effects of plant roots on infiltration rates and hydraulic conductivity are explored in relation to suction response and plant root characteristics.

Materials and methods

Site description and soil properties

This field study was carried out at a flat man-made test plot of 2 m x 2 m located at the site called Eco-Park in Hong Kong. The test plot was made of compacted completely decomposed granite (CDG), a soil type that is commonly found in Hong Kong. CDG material was compacted to an in-situ dry density of 1.8 g/cm^3, which is about 95% of the maximum dry density (i.e., relative compaction RC of 95%). The location of groundwater table (GWT) was determined by a geophysical method, and it was identified at 4.5 m depth. To characterize the CDG, four soil samples were collected at depths of 0.1, 0.2, 0.3, and 0.4 m for determining soil index properties.

The average gravel, sand, fine contents (i.e., silt and clay) of CDG were 9.5%, 83.1%, and 7.4%, respectively. Based on the measured particle-size distribution and Atterberg limits, CDG is classified as well-graded sand with silt (SW-SM; ASTM, 2011).

For measuring the hydraulic properties of unsaturated CDG including water retention curves (WRCs) and hydraulic conductivity function ($k(\psi)$, where is ψ suction), soil column tests were conducted in the laboratory based on the Instantaneous Profile Method (IPM) proposed by Watson (1966). CDG sampled from the site was re-compacted to the identical in-situ dry density (i.e., 1.8 g/cm^3) into a column with diameter of 140 mm and height of 600 mm. The soil column was then subjected to a drying path by exposing it to natural evaporation, during which changes of volumetric water content (VWC) and suction along the column were monitored by four pairs of water content sensors and tensiometers, respectively. The drying test was stopped when suction recorded by any tensiometer reached 80 kPa (i.e., limit of the working range of each tensiometer). Then, ponding with a constant water head of 50 mm was applied on the soil surface to undergo wetting process. Similarly, the associated changes of VWC and suction were recorded. The drying and wetting WRCs were then obtained by relating the measured VWC with the measured suction. More detailed testing procedures were reported by Ng and Leung (2012).

Figure 1(a) depicts the measured drying and wetting WRCs. Each curve was fitted with the equation proposed by van Genuchten (1980) for interpretation. The fitting parameters are given. It can be seen from the drying curve that the air-entry value was ~ 1 – 2 kPa, beyond which VWC dropped substantially. Hydraulic hysteresis is identified. For any given suction, VWC on the wetting curve was about 15% – 20% lower than that on the drying curve. On the other hand, the measured drying and wetting $k(\psi)$s are depicted in Fig. 1(b). Similarly, the van Genuchten (1980) equation was used to fit the experimental data. By setting the values of saturated soil hydraulic conductivity, k_s, (one of the fitting parameters) to be 1.22 x 10^{-6} m/s for the drying $k(\psi)$ and 5.15 x 10^{-7} m/s for the wetting one through statistical regression, a goodness-of-fit of up to 0.983 could be achieved. Although these values of k_s were not measured directly, the method of using the combination of the IPM and statistical regression has been considered to give a reasonable estimation of k_s (Krisdani et al. 2009). These estimated values of k_s is found to be close to the ranges of k_s of CDG from Hong Kong determined by Yin (2009) (from 2 x 10^{-6} m/s to 1 x 10^{-8} m/s) and by Gan and Fredlund (2006) (from 1 x 10^{-7} m/s to 1 x 10^{-8} m/s for CDG samples with particle-size distributions similar to this study). Some reported k_s values of compacted well-graded sand with silt in the literature (Morris and Johnson 1967; Huang et al., 1998; Rahardjo et al., 2004) are also found to be fairly close to the measurement made in this study. Other measured index properties are summarized in Table 1.

Characteristics of selected grass and tree species

In this study, a grass species (*Cynodon dactylon*; known as Bermuda grass) and a tree species (*Schefflera heptaphylla*; known as Ivy tree) were selected for investigation. These species were chosen because of (i) their commonness in the South-East Asia including Hong Kong and India as well as parts of the US at sub-tropical regions (Hau and Corlett, 2003; Frodin et al., 2010); and also (ii) their ability of drought tolerant that may be suitably used for ecological restoration and rehabilitation at warm climates of the world (Carrow et al., 1996; Hau and Corlett, 2003; Hu et al., 2010). Before testing, sods of *Cynodon dactylon* were germinated and grown in 120 mm-thick CDG at a nursery one year in advance. Note that the CDG used was identical to soil type tested in this field study and was re-compacted at the same in-situ dry density. Figure 2(a) shows the overview of the typical grasses (after one year of germination) tested in series Inf1. It can be seen that the shoot length of grass ranged from 87 to 105 mm. On the other hand, the grass roots are fibrous and they have lengths ranging from 86 to 131 mm (i.e., root depth). Similar characteristics of shoot and roots were identified for grasses vegetated in series Inf2 and Inf3. Table 2 summarizes the range, mean and standard deviation of the lengths of grass shoot and roots in all three test series.

Each tree individual tested in this study was also grown in CDG in the nursery for a year. Similarly, the CDG used as the growing medium was identical to that tested in the field. Figure 2(b) depicts the overview of a typical tree individual (after one year of growing) tested in series Inf1. The shoot system of the typical individual consisted of a main stem having a length of 978 mm. It is determined that Leaf Area Index (LAI), which is a dimensionless index defining the ratio of total one-sided green leaf area to projected area of an individual plant on soil surface in plan, of the tree individual was 0.8. A closer view of the roots shows that the root length was 280 mm. A tap root with a diameter of 6 mm was identified. There were clusters of root hair with diameters ranging from 1 – 2 mm, which were mainly responsible for root-water uptake. The observed shoot and roots systems were similarly found for tree individuals tested in series Inf2 and Inf3. Measured ranges, mean and standard deviation of tree properties in all three test series are summarized in Table 2.

Test setup and instrumentation

Figure 3 shows the schematic setup of a typical double-ring infiltration test and the arrangement of instruments for the test plot vegetated with the selected tree species. The setup consisted of an inner ring (0.3 m in diameter), an outer ring (0.6 m diameter), and a calibrated Mariotte's bottle for maintaining water head inside the inner ring. The inner and outer rings were inserted into the ground by 0.75 and 0.15 m depths, respectively. Any gaps between the two rings and the ground were sealed using cement paste to ensure no water leakage during testing. The reason of having a deeper inserted depth of the outer ring is to help reducing any water flow beneath the inner ring towards the lateral direction, and this hence promotes nearly exclusively one-dimensional (1D) vertical water flow. It should be noted that the 1D flow condition in a double-ring infiltration test is an idealization of natural condition of infiltration, where water flow is generally three-dimensional (3D). The idealised 1D flow is useful to isolate the effects of vegetation on infiltration rate and suction distributions from any effects due to 3D flow. The test setup was similar to that described by the ASTM Standard D3385 (ASTM, 2009). The only difference was that grass and tree were transplanted inside both inner and outer rings.

In order to monitor the responses of negative pore-water pressure (PWP) or suction during an infiltration test, an array of three jet fill tensiometers (JFTs) were installed at 0.1, 0.3 and 0.5 m depths. The aim of choosing these installation depths was to quantity the magnitude of plant-induced suction both within (0.1 m) and below (0.3 and 0.5 m) root zones. This would also help identifying any vertical influence zone of suction due to the effects of plant upon ponding. Before installation, the ceramic tip of each JFT was fully saturated with de-aired water, while the plastic tube of each JFT was completely filled with de-aired water in the laboratory. Inside the inner ring, two holes having a diameter (30 mm) slightly larger than that (22 mm) of the ceramic were drilled to the two installation depths. After installation, gaps between JFT and installation hole were backfilled with in-situ soil around the ceramic and then with cement paste for the rest. This aimed to minimize any preferential water flow. It is well-known that air bubbles would accumulate in a JFT due to air diffusion through the ceramic disk. During testing, any observed air bubbles were removed by pressing a jet fill button so that air bubbles can be displaced by water from reservoir stored at the top of the JFT.

Test methods and procedures

In order to investigate any effects of both in-situ soil heterogeneity (i.e., spatial variability) and plant variability on infiltration characteristics, a series of three repeated double-ring infiltration tests (Inf1, Inf2 and Inf3) were conducted. Within the 2 m x 2 m test plot, three double-ring infiltrometers were installed at separate locations with approximately 0.75 m spacing between each other. In each repeated series, infiltration test on bare soil (Inf1-B, Inf2-B and Inf3-B) was carried out first, followed by tests on the same location covered with the selected grass species (Inf1-G, Inf2-G and Inf3-G) and then the tree species (Inf1-T, Inf2-T and Inf3-T). The advantage of testing in such sequence is to eliminate the effects of soil heterogeneity when comparing results between the three surface covers within each individual series. The three repeated tests for each soil surface condition were carried out simultaneously. However, there were difficulties in producing a test plot with a uniform distribution of soil dry density in the field. This is because a much bigger compaction machine was needed to construct the relatively big size of the test plot at the site (compared to the much better controlled of compaction of a smaller sample size in the laboratory). Before testing on the bare soil for series Inf-1 (i.e., Inf1-B), the initial suction at 0.1, 0.3 and 0.5 m depths were 6, 9.5 and 13.5 kPa, respectively. An infiltration test following the test procedures described in the ASTM Standard D3385 (ASTM, 2009) was then performed. Inside both the inner and outer rings, the same constant water head of 0.1 m (the average value suggested by the Standard) was applied using the Mariotte's bottle (Fig. 3). Upon ponding, any changes of (i) water level in the bottle and (ii) suction at all three depths were recorded. The test was run for two hours so as to ensure that the volume of water infiltrated and suction at both depths reached steady state. As a result, infiltration rate (I) at any time interval, dt, during ponding can be determined as follows:

$$I(t)=\frac{1}{A}\frac{dV}{dt} \tag{1}$$

where dV is change of volume of water infiltrated within a given dt; and A is ponded surface area inside the inner ring. The test was conducted during a wet, cloudy summer, when the average solar radiation, air temperature and relative humidity (RH) in air were 8.8 MJ/m^2/day, 16.1 ^{o}C, and 87%, respectively. According to Penman equation, the rate of potential evaporation (PE) is estimated to be 0.1 mm/hr.

After testing on bare soil, infiltration test was then carried out on the same location but vegetated with the selected grass species for test Inf1-G. After growing the grasses one year in advance in the nursery, grass sods including the 120 mm-thick bulk soil (i.e., roots remain intact and alive) were transplanted to the entire test plot of 2 m x 2 m. Since the CDG used for germinating grass sods in the nursery was identical to that tested in the field, transplanting these pre-grown grass sods to form grass-covered soil in the field was considered equivalent to nature germination of grass seeds over the test plot in-situ. After transplanting, the technique adopted by Wang et al. (2007) was used to ensure favourable growth conditions for the grass sods. The grass-covered soil was irrigated every two days over two months so as to maintain the level of average suction similar to the field capacity of the CDG (i.e., 23 – 28 kPa) The duration of two months of frequent irrigation schedule has been shown to be sufficient for plant roots to establish with in-situ soil after transplantation (Shock et al. 2000; Wang et al. 2007). To allow for direct comparisons of test results between bare and grass-covered soil, it is important to have similar initial suction before the start of test Inf1-G. This is because soil having different initial conditions is known to affect both water retention capability and hydraulic conductivity (Ng and Leung, 2012), hence affecting the subsequent infiltration process and the associated suction responses. Therefore, the grass-covered soil was exposed for natural variation until the initial suction at 0.1, 0.3 and 0.5 m depths (7, 8 and 14 kPa, respectively) were close to those recorded in bare soil. This took five days. The identical test procedures described above were then adopted. The test was undertaken under similar climatic condition (solar radiation of 9.3 $MJ/m^2/day$, air temperature of 17.1 ^{o}C, and RH of 81%), which resulted in the rate of potential evapotranspiration (PET) of 0.2 mm/hr according to Penman-Monteith equation.

When test Inf1-G was completed, the top 0.15 m of the soil was excavated for removing all grass roots and it was backfilled with in-situ soil to restore the original ground level. Tree individuals together with their soil/root balls (i.e., the entire root systems remain intact and alive) were then transplanted from pots at the nursery to the site for infiltration tests (Inf1-T). The individuals were distributed uniformly (i.e., same tree spacing) over the entire test plot. Similar to the grass-covered soil, all tree individuals transplanted were also irrigated regularly every two days over two months, based on the technique adopted by Wang et al. (2007). Note that the applied experimental scheme for the tree-covered soil was consistent with some typical and standardized procedures adopted for ecological restoration and rehabilitation of some infrastructure such as slopes, road embankments and landfill cover systems (Hau and Corlett 2003; Urhin et al. 2009). The tree-covered soil was then subjected to natural variation, until initial suction recorded at 0.1, 0.3 and 0.5 m depths (8, 9 and 15 kPa, respectively) were close to those observed in bare and grass-covered soil. This process took three days. Infiltration test was then conducted on the tree-covered soil according to the identical test procedures described above. The climatic condition during the testing of tree-covered soil was similar to that of grass-covered soil, undergoing a PET rate of about 0.2 mm/hr.

For the repeated series Inf2 and Inf3, the above test procedures were repeated identically, but they were conducted on two separate locations of the site. In order to achieve similar initial suction for the two series Inf2 and In3 before testing, the same method described above for series

Inf1 was adopted. Table 3 compares the initial suctions measured at 0.1, 0.3 and 0.5 m depths between the three test series Inf1, Inf2 and Inf3. In each series, the maximum difference of initial suction between bare and vegetated soil is found to be less than 3 kPa.

Measurements of distribution of root area index of tree roots

After testing on tree-covered soil in tests Inf1-T, Inf2-T and Inf3-T, all tree individuals were removed carefully for determining root characteristics (in terms of Root Area Index, RAI) in the laboratory. RAI is an index normalising total root surface area for a given depth range within root zone by plan cross-section area of soil. After removal of each tree individual from the site, soil attached to the root system was washed out carefully. The entire branch of plant roots was clamped and high-resolution images were taken around 360°, which were then superimposed to generate a three-dimensional (3D) picture of a root system. Through image analysis, each full pixel image of 3D root system was discretized into grids, and area in each grid containing roots for a given depth was then determined to obtain RAI.

Figure 4 compares the RAI profiles of three typical tree individuals sampled from the three test series. For the individual tested in Inf1-T, RAI increased almost linearly from 0.35 to 0.80 with an increase in depth in the top 150 mm. This means that there was an increasing number of root hair in deeper depths. Below 150 mm depth, the measured RAI decreased substantially to about 0.18 at the root depth of 300 mm. Similar shapes of RAI profiles were found for the other two individuals, but the RAI of the individuals in tests Inf2-T and Inf3-T were higher and lower than that in Inf1-T at all depths, respectively. The peak RAIs are found at a depth range between 140 – 160 mm for all three individuals consistently. The observed lower RAI in shallow depths may be because the near-surface soil condition is not as favorable as that in deeper depths for root development (López et al., 2001). The near-surface soil is generally drier and warmer (Blight, 1997), which could suppress the root metabolism and its growth (López et al., 2001). On the other hand, the reduction of RAI below 160 mm depth may be because of the increasing significance of overburden pressure in deeper depths, where mechanical resistance for root penetration and growth prevails (Bengough and Mullins, 1990). The measured range, mean and standard deviation of the peak RAI of the ten tree individuals in each test series are summarized in Table 2.

Results and discussions

Observed infiltration characteristics for different surface covers

Figure 5 compares measured cumulative water infiltration with time between bare, grass-covered, and tree-covered soil during the two hours of ponding from series Inf1. In bare soil, water volume infiltrated is found to increase at a decreasing rate. After ponding for two hours, the amount of water volume infiltrated appears to increase linearly with time, indicating that steady-state condition was reached. Similar trend of variation is observed for both grass-covered and tree-covered soil, and it is found that the volume of water infiltrated in these two types of vegetated soil was similar. Although the initial suction between bare, grass-covered, and tree-covered soil were comparable (Table 3), the volume of water infiltrated in both vegetated soil was less than that in the bare soil by up to 50% at steady state. This indicates that the presence of plant roots has a significant effect in reducing the volume of water infiltration.

In order to determine infiltration rate, each measured variation of cummulative water volume infiltrated with time is best-fitted by ordinary least-square method and each best-fitted curve is then differentiated with respect to time (Eqt 1). As shown in Fig. 5, the infiltration rate in bare soil decreased exponentially at a decreasing rate, as expected. At steady state, the infiltration rate approached the laboratory k_s of CDG. For grass-covered soil, the infiltration rate was always lower than that in bare one. The difference was the largest (45%) at the beginning of the test, but it then decreased as ponding progressed with time. When comparing the infiltration rates between grass-covered and tree-covered soil, they appear to have no discernible difference throughout the ponding event.

Effects of natural variability of plants on water infiltration rates

Figure 6 compares the measured upper and lower bounds of infiltration rates between bare and vegetated soil tested in the three repeated series Inf1, Inf2 and Inf3. It can be seen that the infiltration rates measured in bare soil in tests Inf1-B, Inf2-B and Inf3-B exhibited some variations. The maximum difference between the lower bound (from test Inf1-B) and upper bound (from test Inf3-B) of infiltration rates was relatively large during the first 20 min of test, but it reduced gradually as ponding progressed with time. Given that the soil density and the initial suction were similar between the repeated tests, the observed variation is likely attributed to the in-situ soil heterogeneity (i.e., spatial variability) at the three locations tested at the site.

For grass-covered soil, it can be seen that both upper bound (from test Inf3-G) and lower bound (from test Inf1-G) of infiltration rates were lower than those in bare soil. The observed variations of infiltration rate in grass-covered soil are attributed to not only in-situ soil heterogeneity but also natural variability of grass root characteristics. It can be seen that the upper and lower bounds of infiltration rates correspond to the test for grass having the shortest (Inf3-G; 75 mm) and the longest (Inf1-G; 131 mm) root depths, respectively (Table 2). As the root depth of grass increased by 75%, the infiltration rate decreased by up to 100% during the first 20 min of ponding. This seems to suggest that grass with longer roots would have occupied more soil space, and hence blocked more channels for water flow during infiltration.

For tree-covered soil, the infiltration rates are also found to be lower than that in bare soil consistently. The difference could be as small as 5% (compare the upper bound for tree-covered soil and the lower bound for bare soil). Although similar infiltration rate between grass-covered and tree-covered soil is identified in one particular test series Inf1 (Fig. 5), it is revealed in Fig. 6 that the in-situ soil heterogeneity and natural variability of trees could result in higher infiltration rate in tree-covered soil (see upper bound from test Inf3-T) than in grass-covered soil (see upper bound from test Inf3-G), by not more than 10% though. The observed similar infiltration rates between the two different types of vegetated soil may be somewhat unexpected because the grass and tree species have rather distinctive root system (see Fig. 2).

In order to explain this, some grass sods and soil/root balls of tree individuals were taken for measuring soil void ratio, following the steps typically adopted in plant science literature (Liang et al., 1989). It is revealed that the void ratio of soil contained the grass roots (i.e., top 0.1 m) and the tree roots (i.e., top 0.3 m) is quite similar (i.e., 0.53 – 0.62). This is equivalent to RC of 87% – 91%, which is less than the in-situ target of 95%. This is most likely because a substantial volume of soil pore/void was occupied by roots during its growth and penetration. The similar void ratio between two types of vegetated soil indicates that the effects of root occupancy, and hence any associated change of hydraulic properties including hydraulic conductivity (Gabr et al., 1995; Buczko et al., 2007; Scanlan and Hinz, 2010), are likely to be similar. This may explain the close responses of infiltration rate between the grass-covered and tree-covered soil consistently observed in all three repeated series (see Figs 5 and 6). Nevertheless, it should be noted that the measured responses of the two types of vegetated soil were based on the specific design of the experimental scheme adopted in this study. The measured results only reflect the effects of two specific plant species tested at a certain age and at a given atmospheric condition.

Effects of vegetation on soil hydraulic conductivity

At steady state after two hours of ponding, it was identified from the PWP measurements (as shown later) that suctions at 0.1 m depth in all bare, grass-covered and tree-covered soil were zero. With the applied ponding head of 0.1 m (i.e., equivalent to 1 kPa) at the soil surface, it can be estimated that a hydraulic gradient between the 0.1 m thick of soil in all three cases was 10. By Darcy's law, the value of field k_s in each test can hence be determined using the hydraulic gradient and measured steady-state infiltration rates. Note that since the suction measurements made at 0.1 m depth was within the root zones of the two types of vegetated soil, the values of field k_s determined for these two cases would thus reflect any effects of plant roots on the ability of soil to transmit water under saturated conditions. Figure 7 compares the field k_s of bare, grass-covered, and tree-covered soil for each repeated test series. Due to the in-situ soil heterogeneity, the field k_s of bare soil varied from 9.8 x 10^{-7} to 15.8 x 10^{-7} m/s. However, the average value of field k_s (i.e., 12.6 x 10^{-7}) is consistent with the laboratory value (i.e., 12.2 x 10^{-7} m/s) determined by soil column tests (refer to Fig. 1(b)).

As compared to bare soil, it can be seen that the values of field k_s in grass-covered and tree-covered soil are significantly lower. The same trend is observed in all three repeated tests consistently. Because of soil heterogeneity and natural variability of plants, the values of field k_s in both vegetated soil could be lower than that in the bare soil by as high as 6 times. The average estimated value of field k_s of bare, grass-covered and tree-covered soil is 12.6 x 10^{-7}, 6.1 x 10^{-7}, and 6.6 x 10^{-7} m/s, respectively. This further suggests that the presence of vegetation could lower the soil hydraulic conductivity. One possible mechanism is the blockage of water flow channels in soil pore space by roots (Gabr et al., 1995; Buczko et al., 2007; Scanlan and Hinz, 2010). On the other hand, any changes of soil structure, and hence soil pore size, due to root exudation (Grayston, 1997; Traoré et al., 2000) might also contributed to the observed change of field k_s.

Effects of vegetation on measured suction responses

Figure 8 compares the measured variations of suction at 0.1, 0.3 and 0.5 m depths with time between bare, grass-covered and tree-covered soil during ponding in series Inf1. In bare soil, the suction recorded at all depths decreased substantially during the first 60 min of ponding, and they reached steady state after two hours of ponding. All suction at 0.1 m disappeared. When compared to the measurement made at 0.5 m depth, the decrease in suction at 0.3 m depth was greater because hydraulic gradient in shallower depths was relatively higher upon surface ponding. Similarly, no suction was retained at 0.1 m depth in both the grass-covered and tree-covered soil. The decreasing rate of suction at 0.3 m depth between these two vegetated soil was similar, but the suction retained in tree-covered soil was always slightly higher by 1 kPa. This difference is, however, apparent as it is within the measurement accuracy of JFT (±1 kPa). The observed similar suction responses between the two types of vegetated soil, in this particular series Inf1, were in line with the measurements of comparable infiltration rates shown in Fig. 4.

When compared to bare soil, it is revealed that the measured decreasing rates of suction at 0.3 m depth in the two types of vegetated soil were more moderate during the first 60 min of ponding (Fig. 8). This indicates that the hydraulic conductivity should have been reduced when plant roots were present to occupy soil pore space, consistent to the trend of hydraulic conductivity discussed in Fig. 7. Except time zero, suction in both grass-covered and tree-covered soil are found to be always higher than that in bare soil. This is mainly because there was less volume of water infiltrated in both types of vegetated soil, as compared to bare soil (Fig.

5). Another reason may be attributed to the change of soil water retention ability when roots occupy soil pore space and modify soil pore size and its distribution (Scanlan and Hinz, 2010). Although root-water uptake might induce additional suction, it is minimal because the PET rate during the monitoring periods was small (< 0.2 mm/hr) under the wet summer climate, as compared to the observed water infiltration rate of 5 – 145 mm/hr (i.e., equivalent to 1 x 10^{-6} – 40 x 10^{-6} m/s in Fig. 6).

At deeper depth of 0.5 m, similar suction response was recorded between the two types of vegetated soil (Fig. 8). Contrasting to the immediate decrease of suction in bare soil at the same depth, some delayed responses of at least 30 min are found in both vegetated soil. This further suggests the possible reduction of soil hydraulic conductivity due to the presence of plant roots. After ponding for two hours, there were limited decreases of suction (less than 2 kPa) in both vegetated soil. At steady state, suctions in grass-covered and tree-covered soil were at least 50% higher than that in bare soil.

Distributions of pore-water pressure profiles for different surface covers

To further investigate the effects of the grass and the tree species on PWP distribution, the PWP profiles measured in bare, grass-covered and tree-covered soil in series Inf1 are compared in Fig. 9. Before ponding, the initial distributions of PWPs in all three types of soil were close to each other. When compared to the hydrostatic line that represents the GWT at 4.5 m depth, it can be seen that the initial PWP profiles of all three types of soil were substantially higher, suggesting net downward water flow. When the ponding head of 0.1 m was maintained during each test, PWP of 1 kPa was fixed at the ground surface and it is thus added in the figure to suppliment each PWP profile. After ponding the bare soil for two hours, similar PWP increases of 10 kPa were found at all three depths. This suggests that the depth of influence of suction (i.e., negative PWP) after ponding was deeper than 0.5 m.

For the grass-covered and tree-covered soil, the PWP profiles after ponding were close to each other. It can be seen that suction retained at all depths in both vegetated soil were higher than those in bare soil. Higher suction retained in vegetated soil was also observed by Ng et al. (2014), who compared suction distributions in flat silty sand with and without vegetated with grass species *Cynodon dactylon* (the same species as this study) upon one hour of rainfall in laboratory. As shown in the figure, the measured PWPs at 0.5 m depth in both the grass-covered and tree-covered soil changed very slightly. This suggests that the depths of influence of suction in both vegetated soil were below the root zones between 0.3 and 0.5 m depths. This was shallower than that identified in bare soil as there was less water infiltrated in the two vegetated soil. For the laboratory tests reported by Ng et al. (2014), a much shallower depth of influence (within root depth) was found in the vegetated soil after subjecting to a one-hour rainfall with intensity of 100 mm/hr. Although both this field study and the laboratory study tested CDG compacted at the same RC of 95%, the soil type for the latter case was much finer (fine content of 39%), and thus has a k_s value (1.10 x 10^{-9} m/s) one order of magnitude lower than that in the former case (5.15 x 10^{-7} m/s for wetting $k(\psi)$ shown in Fig. 1(b)). Moreover, the duration of the laboratory rainfall test (one hour) was one hour less than that of the field ponding test (two hours). They are likely the two major reasons for the laboratory case to have relatively smaller volume of water infiltrated, and hence shallower influence zone of suction than the field case.

Effects of natural variability of plants on suction retained after ponding

Figure 10(a) compares the final suction retained at 0.3 m depth between bare and vegetated soil in the three repeated test series. After subjecting to two hours of ponding, the suction retained in bare soil was 0 – 1 kPa. On the contrary, it is consistent in all three repeated tests that both grass-covered and tree-covered soil retained suction of at least 2 kPa higher than bare soil, due to the clogging of soil pore space and hence blockage of water flow by plant roots. For grass-covered soil, it can be seen that the amount of suction drop was the least in test Inf1-G, but it was the largest in test Inf3-G. This is because tests Inf1-G and Inf3-G showed the lowest and highest infiltration rates, respectively (Fig. 6). For tree-covered soil, the measured suction drop in test Inf3-T was the greatest (Fig. 10(a)) again because the infiltration rate was the highest between the three repeated tests (Fig. 6). Interestingly, in series Inf2, the final suction retained in tree-covered soil (6 kPa) was remarkably high, even though this particular test did not result in the lowest infiltration rate (Fig. 6). As listed in Table 2, the tree individuals investigated in test Inf2-T have the highest RAI (as compared to those in tests Inf1-T and Inf3-T), which is likely to have modified soil pore-size distribution and soil water retention ability more significantly.

Comparisons of suction measured at the deeper depth 0.5 m between bare and vegetated soil are shown in Fig. 10(b). Unlike series Inf1, suction recorded in both vegetated soil in series Inf2 and Inf3 showed much more substantial reductions during infiltration. This means that due to plant variability, the depths of suction influence zone could be deeper than 0.5 m. Similar to the measurements made at 0.3 m depth, the amounts of suction drop at 0.5 m depth in both bare and vegetated soil were the largest in series Inf3 due to the relatively high infiltration rates. After ponding, the final suction retained at 0.5 m depth in both vegetated soil are higher than those in bare soil by 50% – 150%. When comparing the two types of vegetated soil, the final suction retained in grass-covered soil was generally close to that in tree-covered one.

Summary and conclusions

This study investigates and compares the effects of *Cynodon dactylon* (grass) and *Schefflera heptaphylla* (tree) on infiltration rates, hydraulic conductivity, and suction distributions during a wet summer. Three repeated double-ring infiltration tests were conducted at a vegetated sandy soil, where tensiometers were installed to measure the responses of suction. This allowed hydraulic gradient to be determined for the estimation of hydraulic conductivity for each vegetated soil. Measured infiltration rates and hydraulic conductivity of each vegetated soil were interpreted with suction measurements together with plant root properties, in terms of RAI.

Based on the interpretation of the test results, the infiltration rates and hydraulic conductivity in soil covered with the two selected species were revealed to be always lower than those in bare soil, when soil heterogenity (i.e., spatial variability) and natural variability of plants are taken into account. It is found that although the difference of infiltration rates between the vegetated and bare soil could be as large as 100% at the beginning of tests, such difference was minimal when steady state was reached. When comparing the two types of vegetated soil, the infiltration rate was not always similar. The tree-covered soil could have higher infiltration rates by 10% due to natural variability of tree root properties. At steady-state, it is determined that the average values of hydraulic conductivity of the grass-covered and the tree-covered soil are 6.1 x 10^{-7}, and 6.6 x 10^{-7} m/s, respectively, which are about two times lower than that in bare soil (12.6 x 10^{-7} m/s). This is likely to be attributed to the clogging of soil pore when plant roots are presence in the soil.

Due to the lower infiltration rates and hydraulic conductivity in the two types of vegetated soil, the measured amounts of suction drop were always less than those in bare soil. While some delayed suction drops of up to 30 mins (since ponding commenced) were identified in the vegetated soil, immediate response (within 10 mins) is observed in bare soil. After ponding, the final suction retained below the root zone (at 0.5 m depth) in the vegetated soil are 50% – 150% higher than that in bare soil. Because of the similar infiltration rates and hydraulic conductivity between the tree-covered and the grass-covered soil, the amount of suction retained in the two types of vegetated soil is found to be indiscerniable. Moreover, it is identified that for the tree-covered soil, the final suction retained is higher when the soil was vegetated with the trees having deeper root depth and high RAI (i.e., root surface area).

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Table 1. A summary of measured index properties of completely decomposed granite (CDG) sampled at 0.1, 0.2, 0.3 and 0.4 m depths

Index property	**Measured value/range**
In situ dry density (g/cm^3)	1.78 – 1.82
In situ water content by mass (%)	11 – 17 %
Compaction characteristic	
Maximum dry density (kg/m^3)	1870
Optimum moisture content (by mass, %)	13
Particle-size distribution	
Gravel content (> 2 mm, %)	9.0 – 10.0
Sand content (≤ 2 mm, %)	79.6 – 85.0
Silt and clay contents (≤ 63 μm, %)	5.0 – 10.4
Specific gravity	2.60 – 2.63
Atterberg limits	
Plastic limit (%)	22 – 30
Liquid limit (%)	42 – 46
Plasticity index (%)	16 – 20
Volumetric field capacity (%)	20
Air-entry value (kPa)	~1 – 2
Unified soil classification system (USCS)	Well-graded sand with silt (SW-SM)

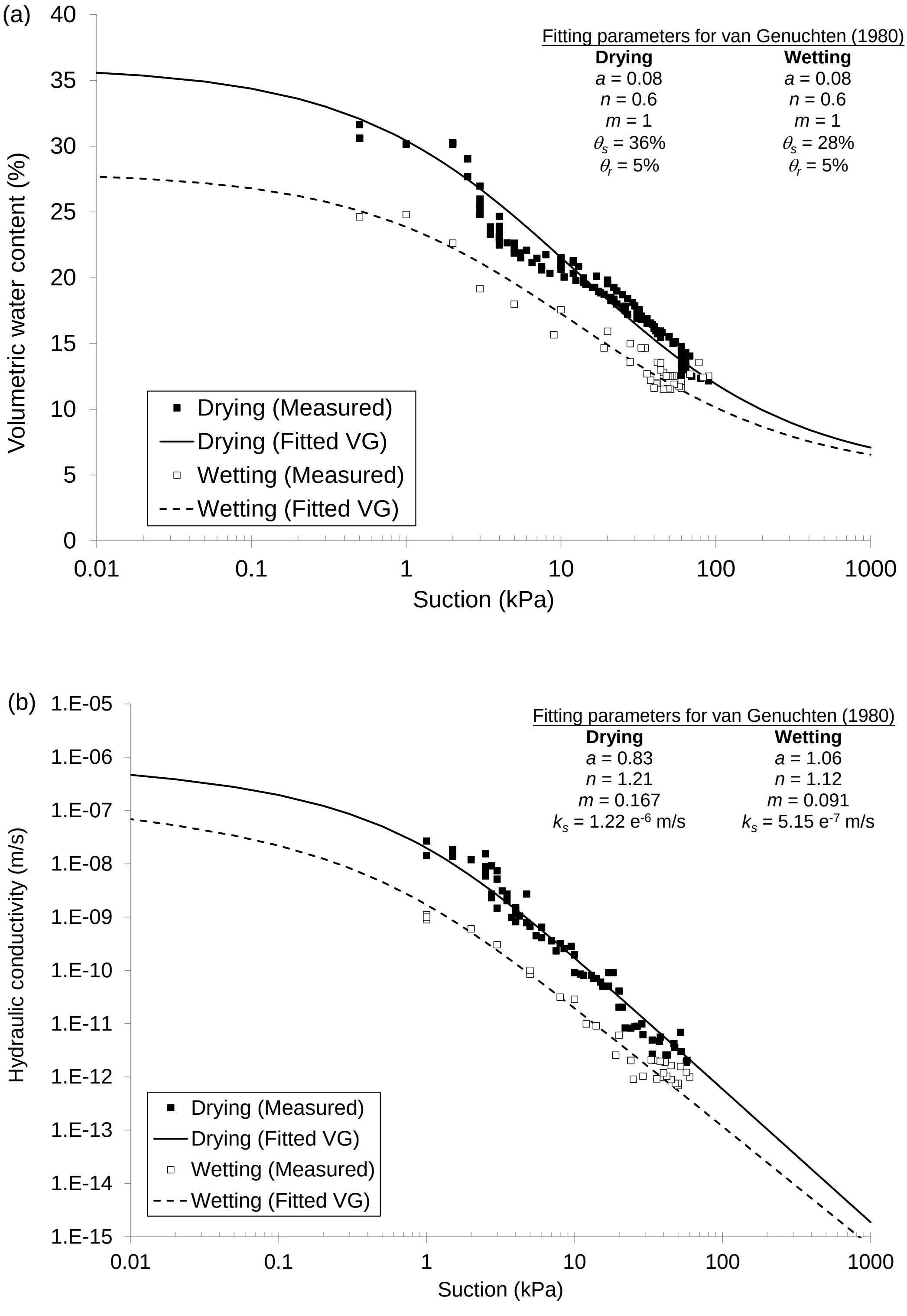
Table 2. A summary of measured characteristics of grass and tree tested in the three series Inf1, Inf2 and Inf3

Plant characteristics	**Inf1**	**Inf2**	**Inf3**
Cynodon dactylon (Grass)	Inf1-G	Inf2-G	Inf3-G
Shoot length (mm)	87 – 105 Mean: 96 S.D.*: ±5	89 – 108 Mean: 100 S.D.: ±6	86 – 106 Mean: 94 S.D.: ±7
Root depth (mm)	86 – 131 Mean: 112 S.D.: ±10	79 – 113 Mean: 92 S.D.: ±10	75 – 108 Mean: 85 S.D.:±8
Scheffllera heptaphylla (Tree)	Inf1-T	Inf2-T	Inf3-T
Shoot height (mm)	950 – 1000 Mean:978 S.D.: ±13	900 – 1100 Mean:1013 S.D.: ±55	800 – 1050 Mean:955 S.D.: ±68
Plant canopy diameter (mm)	110 – 200 Mean:153 S.D.: ±18	100 – 220 Mean:145 S.D.: ±34	90 – 180 Mean:127 S.D.: ±30
Leaf area index (LAI)	0.8 – 1.3 Mean:1.1 S.D.: ±0.16	1.0 – 2.1 Mean:1.8 S.D.: ±0.3	0.6 – 1.7 Mean:1.2 S.D.: ±0.3
Root depth (mm)	262 – 305 Mean:280 S.D.: ±22	254 – 320 Mean:291 S.D.: ±20	211 – 260 Mean:232 S.D.: ±12
Peak root Area Index (RAI) (refer to Fig. 4)	0.64 – 0.94 Mean:0.80 S.D.: ±0.11	0.72 – 1.28 Mean:0.97 S.D.: ±0.15	0.59 – 0.75 Mean:0.68 S.D.: ±0.05

*S.D. stands for standard deviation

Table 3. A summary of initial suctions in each series before infiltration tests

Test series	Measured initial suction (kPa)								
	Bare (B)			Grass (G)			Tree (T)		
Depth (m)	0.1	0.3	0.5	0.1	0.3	0.5	0.1	0.3	0.5
Inf1	6	9.5	13.5	7	8	14	8	9	15
Inf2	5	11	16	9	10	17	8	11	17
Inf3	8	12	17	10	11.5	18	11	12	17.5



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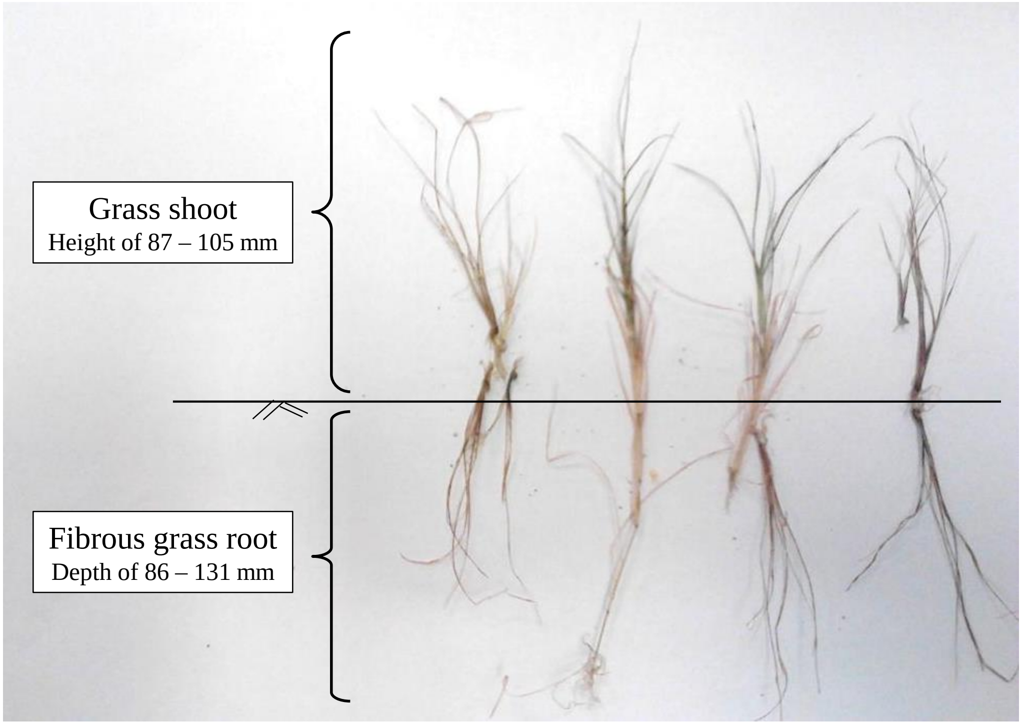
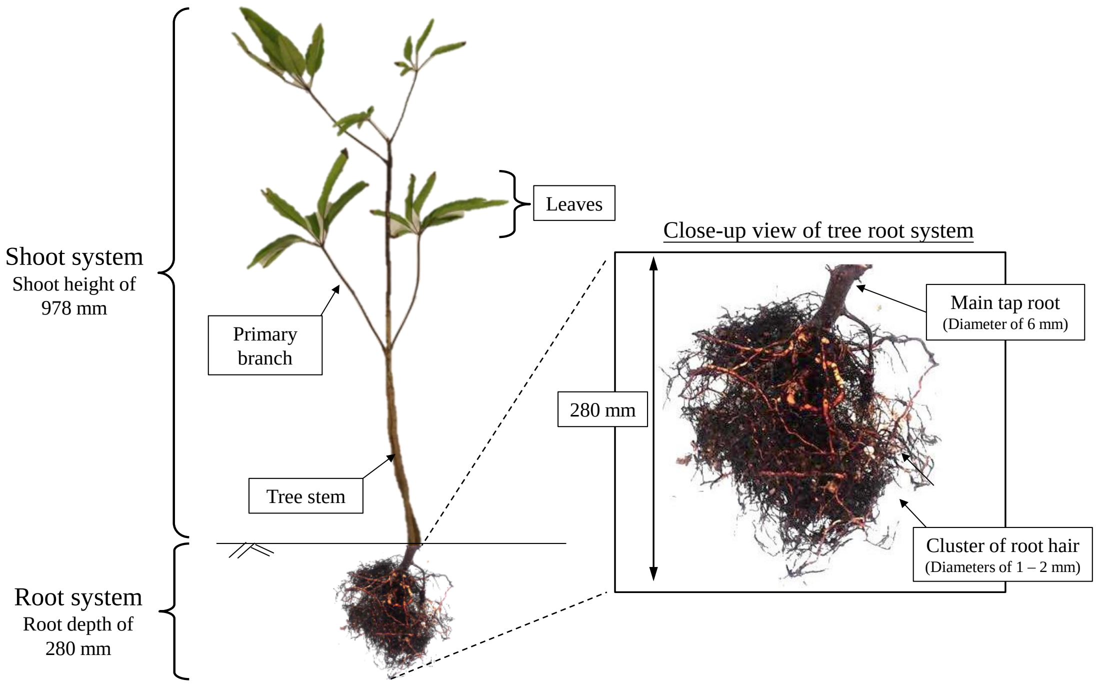
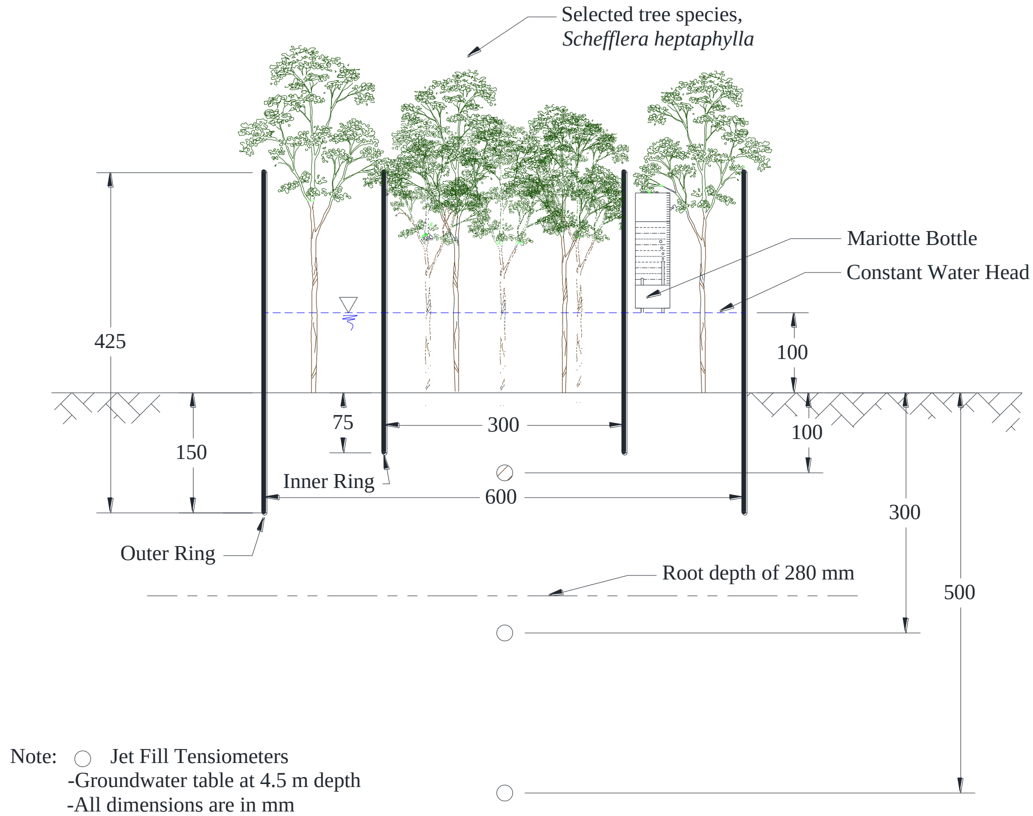


(a)



(b)

Fig. 2 Overview of typical shoot and root systems of the selected (a) grass species, *Cynodon dactylon*, and (b) tree species, *Schefflera heptaphylla* tested in series Inf1



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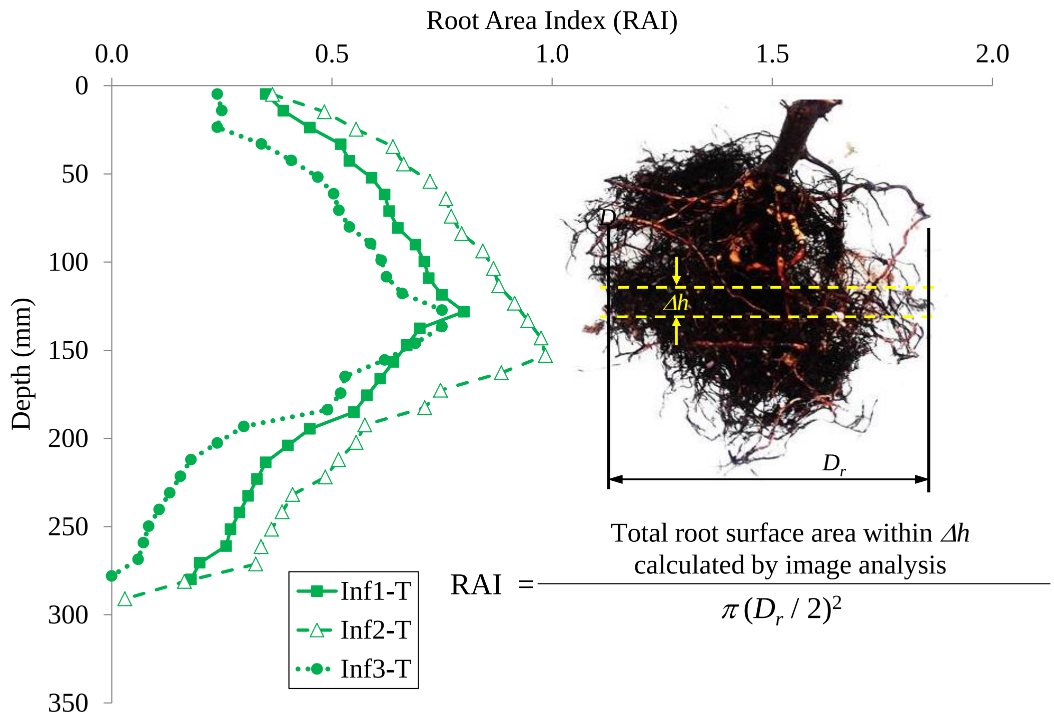

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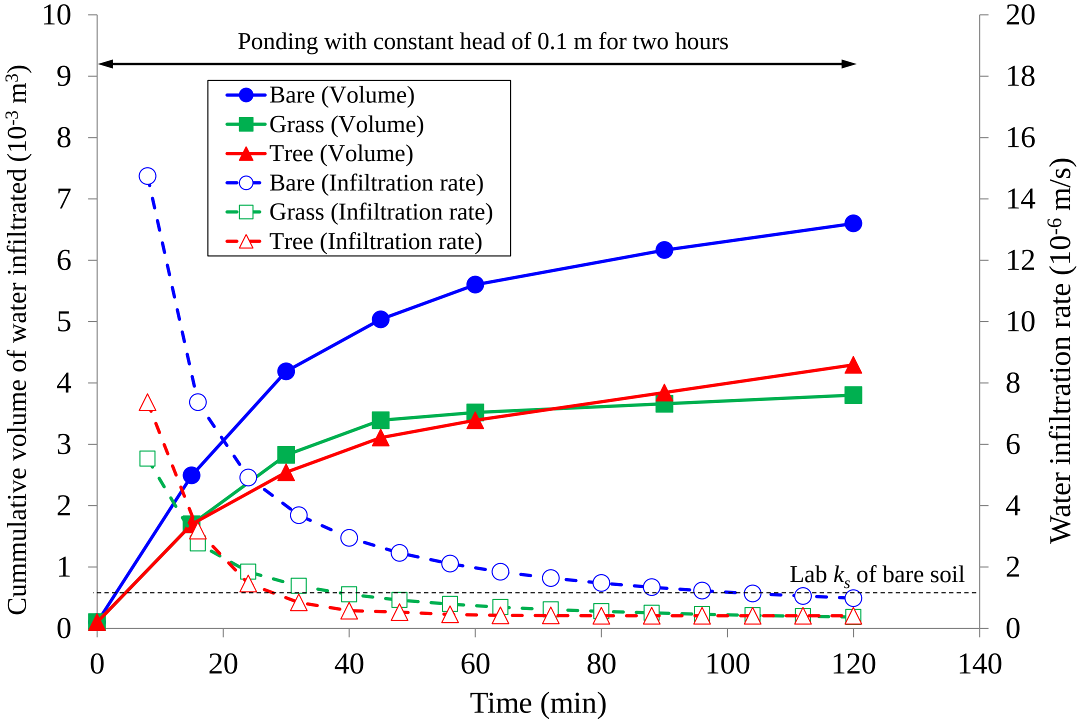

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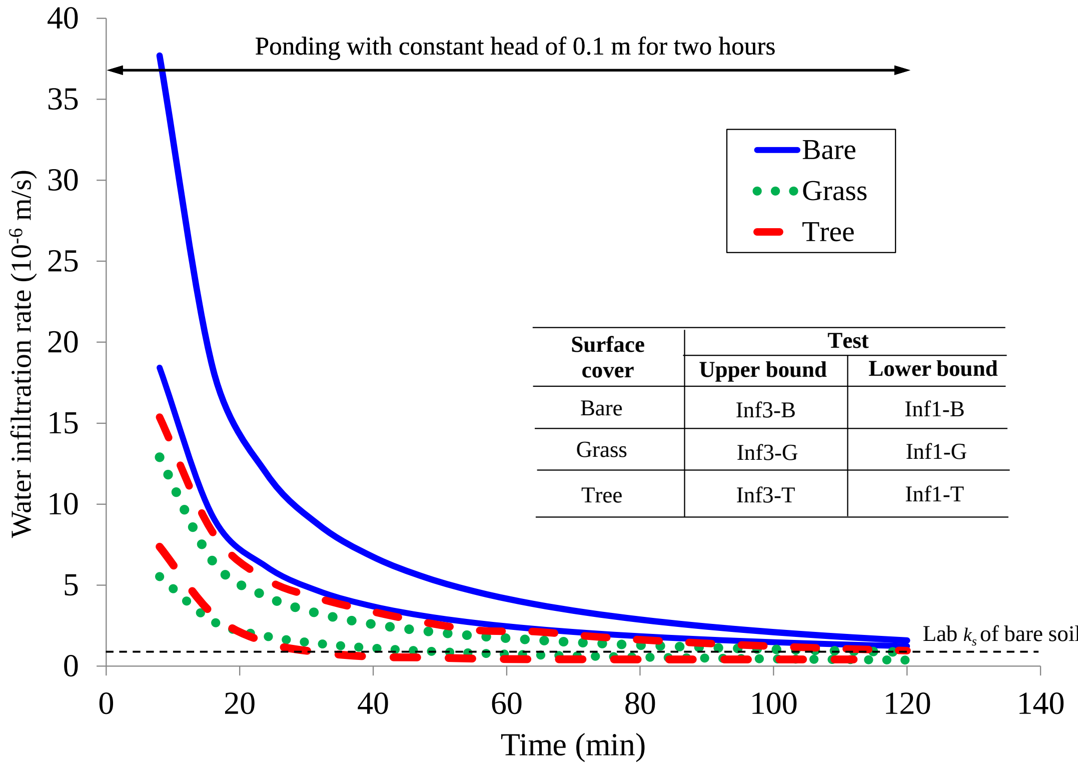

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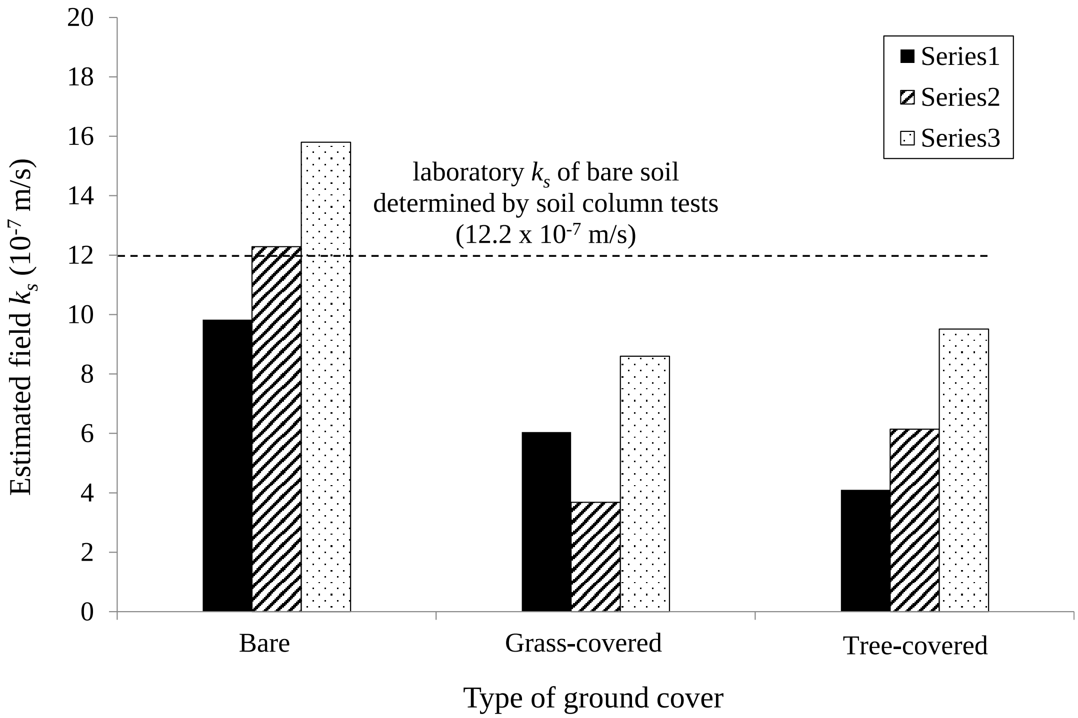
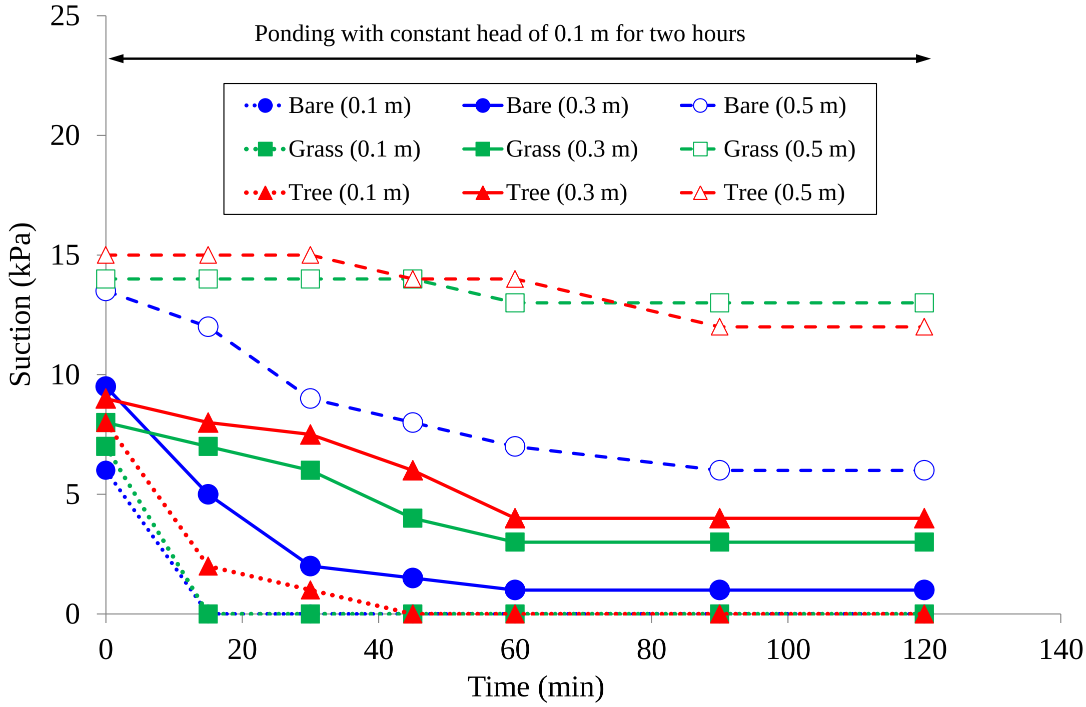


Fig. 7 Estimated field saturated hydraulic conductivity, k_s, of bare and vegetated soil



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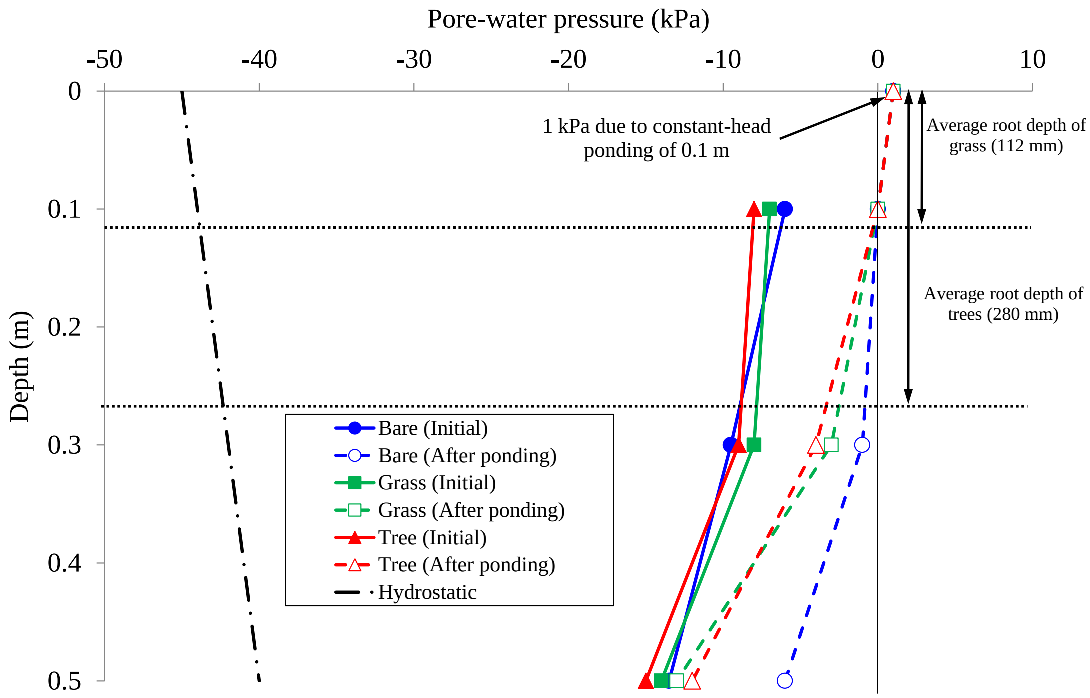

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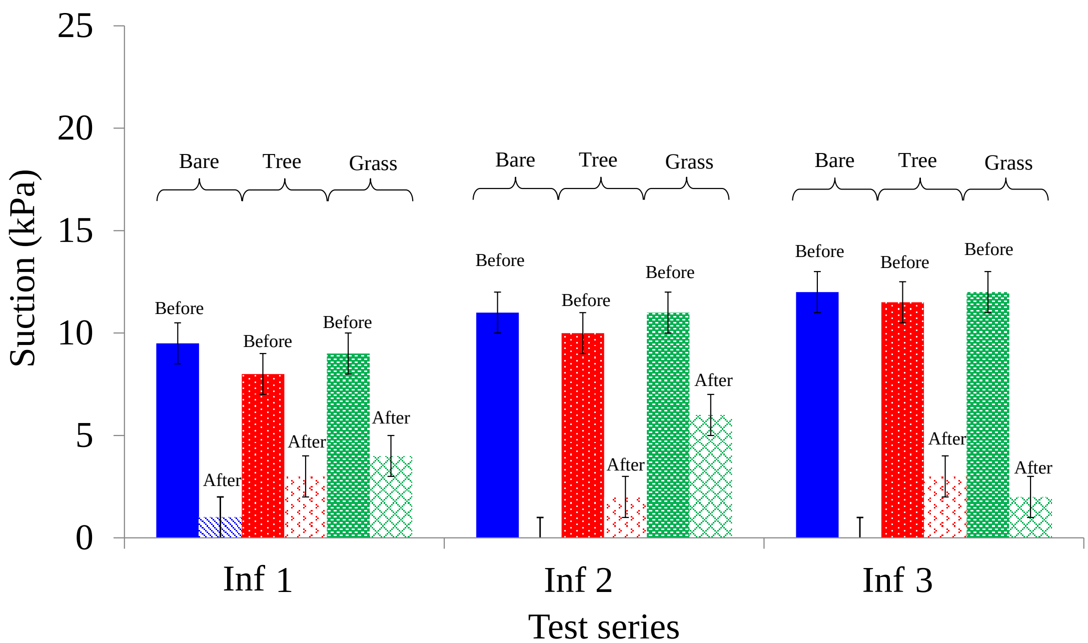
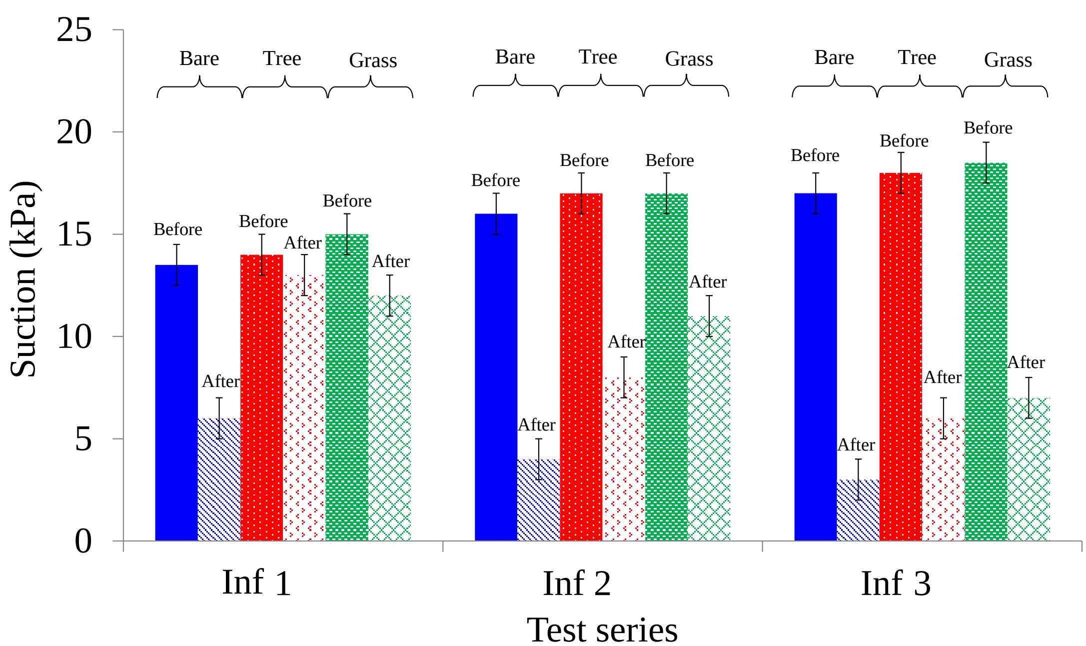


(a)



(b)

Fig. 10 Comparison of final suction retained at (a) 0.3 m and (b) 0.5 m depths after two-hour of ponding between each type of soil in the three repeated tests